400kV TRANSMISSION SYSTEMS IN THE SOVIET UNION.

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I. The Importance of 400 kv Lines in the Power Economy of the U.S.S.R.

The development of the power industry in the Soviet Union, the interconnection of power systems, the construction of large hydro and thermal stations are all closely associated with the creation of high-voltage transmission network and inter-system tie lines, and with the problem of increasing the transmitting capacity and the length of transmission lines. The extent and speed with which the Soviet power industry is developing and the enormous area of the country are factors that require the transmission of power over long distances.

After the 220 kv transmission voltage was introduced into service in the early thirties, extensive theoretical, experimental and design work was started in the U.S.S.R. to develop the use of a higher voltage of 380-400 kv. This work was interrupted by the war. After the end of the second world war, it was got under way with renewed energy. The good results obtained from the work made it possible in 1949-1950 to decide on constructing 400 kv long-distance transmission lines which were to transmit power to Moscow from the large hydroelectric stations being built on the Volga. The construction of the Kuibishev-Moscow transmission line was started in 1952. The line was put into operation in the spring of 1956. The construction of the Stalingrad-Moscow and Kuibishev-Urals 400 kv transmission lines will be completed in 1958-1959.

The development of the power industry put forth the problem of creating a consolidated power system in the European part of the U.S.S.R. in the course of the current five-year period. During the first stage of development of this system, it will be necessary to transmit power in one direction from the region of large power resources to load centers that have insufficient local power resources. This power, to be transmitted over a distance of 1,000 kilometers, is of the order of 1 to 1.5 million kw. It is also necessary to build large 400 kv intra-system circuits within the big power systems in the central, southern and Ural regions of the country, and finally to create inter-system tie lines with large transmitting capacities. These problems can be solved by 400 kv transmission lines; each circuit of a 400 kv transmission line should be capable of transmitting at least 500 to 750 MW.

In the system of the consolidated power economy, 400 kv lines have several functions:

a) to transmit large blocks of power with a capacity factor of 4,500 to 6,500 hours per year from large hydroelectric and thermal stations to power deficit areas;

b) to transmit power from one time zone to another;

c) to transmit reserve power in case of equipment repair and fault conditions.

As a rule, the 400 kv lines carry out all three functions. However, for certain lines, such as the Kuibishev-Moscow and Stalingrad-Moscow lines, the transmission of large blocks of power in one direction over long distances is characteristic.

Table I.

Transmission line	Number of circuits	Length, km	Transmission capacity, million kw	Energy transmitted yearly for average hydro conditions, billion kwh	Remarks
1	2	3	4	5	6
Kuibishev-Moscow	2	a) 815 b) 890	1.5	6.0	Put into servic in 1955
Stalingrad-Moscow	2	1,000	1.5	8.0	Under construction
Kuibishev-Urals	1	1,050	1.0-0.75	4.0	Ditto
Stalingrad-Donbas	1	500	0.75	4.0	±400 kv d.c. line
Moscow ring	1	215	-	-	Under construction

By 1960 there will be 5,000 kilometers of three-phase 400 kv line constructed in the European part of the U.S.S.R. as well as 500 kilometers of 800 kv d.c. line and 17 substations for the 400 kv lines. The capacity of the consolidated power system will reach 30 million kilowatts in 1960.

The second stage in construction of the 400 kv network in the European part of the Soviot Union will be completed during the seventh five-year period from 1961 to 1965. Additional 6,000 - 7,000 kilometers of 400 kv line and 25 step-up and step-down 400 kv substations are to be constructed. The capacity of the consolidated power system in the European part of the Soviet Union will be brought up to 50-60 million kilowatts by the end of this period.

Alongside with the development of 400 kv lines in the European part of the U.S.S.R., similar construction is planned for in the Asiatic part of the Union. First of all, beginning with the current five-year period, 400 kv lines will be constructed to connect into one system the power stations in the Irkutsck, Krasnojarsck, Kusnetsck and Novosibirsck districts, which include the hydroelectric stations being built on the Angara (the Irkutsck and Bratsck Stations), on the Enysei (the Krasnojarsck Station) and the big thermal stations in the Kusbass.

II. Technical Problems of 400 KV Lines

A. Transmission Scheme

The transmitting capacity of one circuit of a 400 kv line should not be lower than 500-750 MW. Since the economical current density for aluminum-steel conductors is from 0.5 to 0.6 amperes per mm^2, the cross section of the current carrying aluminum part of the conductor must be at least 1200 to 1600 mm^2 per phase.

The necessity of keeping the diameter and cross section of the conductors within practical limits, of reducing the line reactance, the corona losses and the radio interference determined the use of bundle conductors. In Soviet practice, the phase bundle is composed of three parallel conductors spaced at the apexes of an equilateral triangle, which side length is from 400 to 600 mm.

For these conditions, the cross section of the aluminum part of a single conductor is from 400 to 480 mm^2 for 400 kv lines in service, in construction, and in design.

The most difficult problem encountered in long-distance a.c. transmission is the stability of parallel operation of power stations connected through the long transmission line. Calculations and studies carried out on electrodynamic system models, and particularly the experience gathered from the first few months of operating the Kuibishev-Moscow line, confirm the possibility of stable operation for a 400 kv line 800 to 1,000 km in length while transmitting from 500 to 750 MW per circuit if several measures are taken to increase the stability, such as:

a) the use of high-speed electronic excitation regulators for the synchronous generators that react not only upon a change in the current and voltage, but on their derivatives as well (the so-called "strong acting" regulators);

Much of operating experience has been gathered from the operation of high electronic excitation regulators for synchronous machines which were developed in our country in the thirties. If the first types of electronic excitation regulators could maintain the transient e.m.f. of the generators constant during transients, the "strong action" regulators designed for the Kuibishev-Moscow transmission showed during the tests that they as a minimum could maintain constant the terminal voltage of the synchronous machine. This circumstance made it possible to raise the initial transmission capacity of the double-circuit Kuibishev-Moscow and Stalingrad-Moscow lines from 1.15 to 1.5 million kilowatts each.

b) The design of water wheel generators for the large hydro-electric stations in accordance with special technical requirements (reduced transient reactance, increased ceiling value and rate of rise of the excitation, increased inertia constant; (this measure is used only for hydroelectric stations connected to the most heavily loaded transmission lines, namely, the Stalingrad and Kuibishev Stations); the reduction of the reactance of 400 kv power transformers; the use of autotransformers instead of step-down transformers;

c) the use of bundle conductors for 400 kv lines in order to reduce the line reactance;

d) the installation of intermediate switching stations every 200 to 250 kilometers for sectionalising double-circuit lines;

e) the use of series capacitor compensation;

The degree of the compensation is not to exceed 40% because of limitations imposed by the requirements of reducing internal overvoltages and increasing the reliability of relay protection. The good results mentioned above, which were obtained in testing the "strong action" electronic excitation regulators, not only permitted to increase the transmission capacity of the 400 kv Kuibishev-Moscow line, but also allowed the series capacitor compensation to be reduced from 40% to 33%. The line Kuibishev-Urals is to have series capacitor compensation of 30%, while for the Stalingrad-Moscow line this figure is 25%. Thus, for the 400 kv lines designed in the Soviet Union, there is a tendency to employ capacitor compensation moderately.

f) the use of synchronous condensers at the intermediate switching stations along the line route;

These condensers are equipped with "strong action" excitation regulators, whose function is to maintain the voltage on the 400 kv buses of the intermediate switching stations during normal operation of the transmission line, and especially during faults. The question of using synchronous condensers at the intermediate substations as a means of increasing the stability of long-distance transmission is given special attention in the Soviet Union. The installation of two 75 MVAR synchronous condensers at each switching station is provided for the Stalingrad-Moscow transmission line.

g) the use of high speed circuit breakers and relays taking a total of 0.10 to 0.12 seconds to clear faults on the 400 kv line;

h) the installation of load resistors on the 400 kv buses of large hydroelectric stations, which are automatically switched on to brake the generators in case of a sudden load dropping.

Shunt reactors are provided to ensure normal operating conditions for the line, and to reduce the losses and the internal overvoltage level. It is expedient under certain load conditions to vary the number of shunt reactors connected so as to regulate the transmission voltage and the flow of reactive power. The transmission line Kuibishev-Moscow during the first period of its operation will not have step-down transformers at the intermediate switching stations. An analysis of the problem, where to install the shunt reactors at the step-up substation, indicated that it is more advantageous to connect them to the 400 kv side. Therefore, this transmission line as well as the Kuibishev-Urals line has all its shunt reactors designed for installation on the 400 kv side. The conditions for the Stalingrad-Moscow line are somewhat different. Here, three intermediate transformers substations of large capacity will be put into service at the same time as the line itself, and the shunt reactors will be installed on the 110 or 220 kv sides.

The connection diagram, the general layout and the switchgear design for the 400 kv switching stations definitely provide for the possibility of expanding them into 400/110 or 400/220 kv receiving substations. The time required for converting a switching substation into a step-down substation is determined by the power demand of the adjacent area. In certain cases it is already necessary at the time the line is being constructed to build intermediate receiving substations as on the Stalingrad-Moscow line.

The insulation levels of the 400 kv network are determined by the following conditions:

the neutrals of 400 kv power transformers are solidly grounded ;

the 400 kv line is protected along its entire length from direct lightning strokes by two ground wires ensuring a protection angle of 15 to 20°;

the grounding resistance of the tower usually is up to ten ohms, for normal soil conditions;

the substations are protected from direct lightning strokes by diverters;

the internal overvoltage level does not exceed 3 times the peak phase voltage.

In accordance with the above mentioned the following test voltages were adopted:

the three-shot 1.5x40 microsecond full wave impulse voltage for the line insulation has a peak value of 1800 to 2000 kv, and that for the substation insulation 1500 kv;

the 50 cycle wet flashover voltage for the line insulation is equal to 775 kv r.m.s., and that for the external substation insulation 700 kv r.m.s.;

the one-minute 50 cycle withstand voltage for the internal insulation is equal to 700-750 kv r.m.w., and that for the external insulation 850 kv r.m.s.

B. Transmission Line

One of the most important specific features characterising 400 kv lines is that: the line has to be more reliable, since its increased capacity and higher cost limit the possibility of constructing double circuits in one direction. It is significant to note that in the European part of the Soviet Union only the Kuibishev-Moscow and Stalingrad-Moscow lines transmitting the largest loads are double circuit lines. All the other lines being designed and constructed at the present are single circuit lines. The design of line structures is more difficult for lines of this voltage because of the increased load on the tower due to the use of bundle conductors, greater electrical clearances, considerable dynamic forces on the tower in case of conductors rupture, etc.

Special technical requirements are imposed on 400 kv lines design in the Soviet Union that differ from the standards for 110 and 220 kv lines in that certain specifications are made more severe.

For example, heavy weather conditions occurring once in 15 years are assumed for the design of 400 kv lines instead of occurring once in 5 years taken for lower voltage lines.

The present regulations for 400 kv lines take into account dynamic forces acting on the tower in case of conductors rupture. Requirements for the calculations of metal structures are made more severe; for certain conditions, the allowable tension in the metal of the towers is reduced, etc.

Increased loads on the towers and foundations of 400 kv lines already at the first stage of the design work necessitated searching for ways to reduce these loads. The first step taken in this direction was the use of an aluminum-steel conductor with reduced steel content. The ratio of the steel cross section to the aluminum cross section for the 400 kv lines conductor is 1 to 8, instead of the usual ratio which lies between 1 to 4.4 and 1 to 5.1 for 110 and 220 kv lines conductors. A new series of reduced weight conductors were developed having an aluminum cross section from 272 to 712 mm^2. This permitted to reduce the expense of steel for towers and of concrete for foundations and to reduce the cost of the line.

The aluminum-steel conductors have a maximum design stress of 8 kg/mm^2 for the aluminum. The actual safety factor for the reduced weight conductors is not lower than 2.75.

Reduction of the design loads for the suspension towers was an exceptionally important measure in obtaining an economical design for the 400 kv line, since these towers comprise 90% of all the towers used. Suspension towers for all 400 kv lines in the Soviet Union are calculated only on the basis of normal operating conditions when accounting for forces that are present with all the conductors intact. The weight of the wires, insulators and sleet and wind pressure determine the weight of the suspension tower, which should be equally stable in the longitudinal and transverse directions. There are several ways of eliminating forces in the suspension tower that arise in case of conductors rupture, such as the use of releasing clamps or clamps with limited holding strength. In all cases, the force on the suspension tower for breaks in all three conductors of the phase bundle should not exceed 1.5 to 2.0 tons. This is the force at which the releasing mechanism operates; it is also equal to the withstand strength of the element holding the three conductors of the bundle in their clamps. The first 400 kv lines in the U.S.S.R. were equipped with special releasing clamps designed for a phase bundle of three parallel conductors. The releasing mechanism operates selectively. This mechanism does not free the wires for breaks in one or two conductors of the phase bundle since the forces that arise in this case are not dangerous to the tower. However, it definitely frees the wires when all three conductors of one phase bundle break irregardless of the order. The releasing mechanism (fig.10) successfully passed tests on the 400 kv stand and excellently functions on the Kuibishev-Moscow line, not once having incorrectly operated.

The negative side of using releasing clamps is the necessity of having to use strain towers (or more usually angle-strain towers) every 7 to 10 kilometers to limit the line section in which the wires may fall to the ground when all three conductors of a phase bundle break. In spite of the fact that the probability of all three conductors breaking is quite small, and that such a break may come about only due to external causes, nevertheless, the use of releasing clamps requires the installation of train towers.

A 400 kv line has been designed that allows strain towers to be eliminated. In this line, releasing clamps are replaced by clamps having a limited holding strength. Therefore, when conductors break, they do not fall to the ground but slip in their clamps. This also limits the force applied to the suspension tower for broken conductors. At the present time, these newly designed clamps are being tested on experimental line sections.

Eliminating strain towers reduces the expenditure of metal for towers by 3 to 4%, and of insulators by 20%. It also considerably reduces the concrete expenditure for foundations.

Determining the most advantageous span between towers and height of the towers is very important in designing the line structures. It is also important from the standpoint of obtaining the best possible technical and economic characteristics for the line. Detailed investigations of this question showed that the economical span is 400 meters, and the height of the suspension tower to the point where the insulators are hung is 27 meters. These figures are pertinent to the European part of the Soviet Union, and also when the common type ACO 400/60 aluminum-steel conductors are used.

After comparing the design of many types of suspension towers, a H-frame suspension tower was adopted for the first 400 kv line Kuibishev-Moscow. This tower has pyramidal posts solidly anchored to their foundations and hinged to the cross arm. The distance between adjacent phases is 10.5 meters. A suspension tower for the Kuibishev-Moscow line, which uses ACO 480/60 conductors, weighs 7.3 tons. Type CT-3 steel is used having a yield point of 2400 kg/cm^2 and a rupturing strength of 3900 kg/cm^2. The wind velocity adopted in designing the line is 25 m/sec, which is equivalent to a pressure of 40 kg/m^2 along the projection of the conductor and 55 kg/m^2 on the tower surface. The following foundations are used for the towers:

for firm dry soil - 12 m^3 packed foundations (52% of the towers);

for loose soil - metal footings with reinforced concrete slabs (13% of the towers);

for poor soil containing water - all concrete massive foundations (35% of the towers).

The same type of suspension tower will be used for the Stalingrad-Moscow line. However, considering the more severe weather conditions along the right-of-way of this line, 90% of which passes through the open steppes, the weight of the tower was increased to 8.6 tons. The design of foundations for the suspension towers in the new lines under construction allows work to be carried out throughout the year. These foundations come either as prefabricated reinforced concrete mushroom shape footings (8 footings, each 1.16 m^3) or as reinforced concrete piles (8 piles 0.4x0.4x7.0 meters per tower).

For the lines Kuibishev-Urals, Votkinsk Hydroelectric

Station-Urals and for the 400 kv lines in Siberia passing through mountainous and forest areas a new type of H-frame suspension tower has been developed.

This tower is supported by steel wire guys and its ports are hinged to their foundations.

These towers economise about 16% of the metal, simplify the construction of foundations and reduce their volume from 8-9 m^3 per tower to 3 m^3. This is an important factor for these regions where transportation facilities are poor. The use of towers with guys is considered permissible along forest and hilly rights-of-way, where there is no danger of the guy wires to be damaged by tractors and other agricultural machinery.

Twin-circuit 400 kv suspension towers are used only when the right-of-way is crowded and each circuit cannot be suspended on a separate tower, since it involves extra metal expenditure for the towers.

The insulators of supporting strings are of the porcelain suspension type. They can take an electromechanical test load of 7 or 8.5 tons. There are 20 to 22 insulators in a string.

The angle-strain towers with strain insulator strings are of the bar type for all the lines under construction. This is the cheapest of all types of 400 kv angle-strain towers.

Angle-strain towers are installed on solid all concrete foundations, and where there is good soil, on packed foundations and prefabricated reinforced concrete footings.

Very severe requirements are levied on the design of 400 kv angle-strain towers. They are to be capable of operating as dead-end towers, and also of taking on the load when two phases (6 conductors) covered with sleet are broken.

The weight of angle-strain towers varies from 23 to 27.5 tons depending on the angle.

The insulators for the strain strings are made of porcelain and are 320 by 200 mm in dimension. They are tested with an electro-mechanical load of 11.0 tons. The three conductors of the phase bundle are attached to the angle-strain tower through a group of three parallel strain strings each containing 22 insulators.

In the 400 kv lines without strain towers and strings, angle H-frame towers have been developed providing an angle of up to 20°. The conductors are attached to these towers through a suspension string.

The technical and economic features of the 400 kv lines being designed and constructed in the Soviet Union are given in table II.

C. 400 kv Substation

The bus arrangements for the 400 kv step-up, step-down and intermediate sectionalising substations are primarily determined to ensure reliable operation of the transmission system as a whole and also to reduce the cost of construction. A comparison of several possible schemes from this standpoint led to the use of economical and at the same time reliable triangular and square schemes as well as the "transformer-bus" arrangement for the greater majority of 400 kv installations (with up to 5-6 elements connected).

The 400 kv receiving substations located near large load centers transform the power down to 110 kv and distribute it at this level within a radius of 30 to 50 km. These substations usually have two transformer or autotransformer groups rated at 270 MVA each.

For a less concentrated load and also for reverse operation of the substation, a transformation of 400/220 kv is used and one or two autotransformer groups are installed at the station which are rated up to 500 MVA. The 400 kv transformers and autotransformers are always equipped with booster transformers with tap changing under load.

In designing the 400 kv outdoor switchgear for the substations of the Kuibishev-Moscow line special attention was paid to ensure reliable operation of the equipment and to provide for its convenient installation and repair.

The 400 kv outdoor switchgear comes with metal portal supporting structures and external main buses.

A bay is 28 meters wide; a line-bay is 161 meters long. The distance between phases is 6 meters.

The buswork for a phase consists of two bare copper cables, each 300 mm^2 in cross section, arranged horizontally 400 mm from each other.

The design of 400 kv outdoor switchgear for the subsequent transmission systems was reviewed and simplified taking into consideration the experience gained from the construction, installation and operation of the first 400 kv substations. This new type of switchgear will be used for the 400 kv Stalingrad-Moscow and Kuibishev-Urals transmission systems. It gives a 20% saving in the material for the structures and in the cost of constructing and installing the switchgear.

The arrangement of the 400 kv substation depends on the number of outdoor switchgear units for various voltages, the way the transmission line and railroad approaches the station, and also on the terrain in the substation area.

For large substations with three voltages of 400, 220 and 110 kv a frontal arrangement is used. For substations with only two voltages, 400 and 110 kv or 400 and 220 kv, a closed arrangement is frequently used where one outdoor switchgear is placed in back of the other and the power transformers and synchronous condensors are installed in the middle along the railroad tracks.

All of the equipment for the 400 kv substations is supplied by the electrical industry of the Soviet Union. Brief characteristics of the main 400 kv equipment are given below.

Step-up transformers - Rating 370 MVA in three-phase group (3 times 123.5 MVA); voltage 13.8 /420 or 13.8/121/420 kv delta-wye-wye connection; neutral on 400 kv side grounded either solidly or through small resistor; short circuit reactances HV-MV -19.5%; HV-LV - 14.5%, MV-LV - 5.5%; water cooled with forced oil circulation.

Step-down transformers - Rating 270 MVA in three-phase group (3 times 90 MVA); voltage 410/115/11 kv; neutral on 410 kv side solidly grounded; wye-wye-delta connection; short circuit reactances: HV-MV - 13%; HV-LV - 19%, MV-LV - 5%; air cooled.

Step-down autotransformer - 1) Rating 270 MVA in three-phase group (3 times 90 MVA); voltage 410/115/11 kv; neutral on 410 and 115 kv sides solidly grounded; 410/115 kv windings connected in wye, 11 kv winding connected in delta; booster transformer for tap changing under load connected in neutral 410/115 kv windings; short circuit reactances; HV-MV -10.5%, HV-LV - 19.5%; MV-LV -9.0%; air cooled.
2) Rating 500 MVA in three-phase group (3 times 167 kva); voltage 420/242/11 kv; neutral of 420/220 kv windings solidly grounded; 11 kv winding connected in delta; short-circuit reactances: HV-MV-10.5%; HV-LV-15.5%, MV-LV-12.5%; air cooled.

400 kv Circuit Breaker - 1) Air blast with disconnector; rated current 2000 a; interrupting capacity 10,000 MVA; disconnecting time 3 cycles.

2) Ditto, but with interrupting capacity of 15,000 MVA.

400 kv Disconnecting Switches: knife blade, rated current 2000 and 1500 a; a.c. motor drive.

Potential Transformer Cascade type, transformation coefficient $\frac{420,000}{\sqrt{3}} / \frac{100}{\sqrt{3}}$ 100 v; power consumption 300 va, accuracy class 0.5.

Current Transformer Cascade type, transformation coefficient 2000-1000-500/1a.

Shunt Reactor Single phase rating 50 MVA; voltage 400 kv; neutral solidly grounded; air cooled.

400 kv Coupling Capacitor Stack type, capacitance 6250 pf.

Carrier Frequency Trap Suspension type, self inductance 2 mh, rated current 1850 a.

III. First Results of Operating 400 kv Kuibishev-Moscow Line

The first circuit of the transmission line was constructed by the fall of 1955, except for the troublesome section in the Djigoulee district. By that time, construction and installation work at the 400/110/220 kv Eastern substation in Noginsk had also been completed. This allowed research work and tests to be carried out on the line during the winter of 1955/1956 when applying 400 kv to it from the Moscow end.

The program of this work included measuring the line parameters, checking the operation of equipment and apparatus, and measuring voltages and currents for different operating conditions of the line. By the spring of 1956, the Djigoulee section of the line was constructed and the 400 kv outdoor switchgear at the Kuibishev station was installed. This enabled the test program to include two-way feed of the transmission line.

In April 1956 the necessary tests were made and the first circuit of the 400 kv Kuibishev-Moscow line 815 km ling was put into service. In October 1956, the second 400 kv substation at the Moscow end was put into service as well as the 77 km, 400 kv line Noginsk-Northern. In the beginning of December 1956 the second circuit of the transmission line was put into service.

For eight months in 1956 the 400 kv line transmitted 1750 million kwh from Kuibishev to Moscow. The maximum power transmitted through one circuit was equal to 500-520 MW. After the second circuit was put into service in December 1956 the transmission capacity increased and in February 1957 over 800 MW was transmitted over the two circuits.

Actual system tests of the transfer capacity of one circuit of transmission line from the standpoint of steady state stability showed that without series capacitor compensation and with only standard excitation regulators on the generators the steady-state stability limit for a voltage level of 420 kv is equal to 560-580 MW. Setting the steady state stability factor at 10 to 15%, the transfer capacity of one circuit under these conditions is equal to 500-470 MW.

The line parameters were determined experimentally in the course of this test program. The measured values of the phase-to-ground and phase-to-phase capacitances per kilometer of line are C_{11}=0.00678 and C_{12}=0.00103 MFd/km. The working capacitance C_w evaluated as $C_{11}+3C_{12}$ is equal to 0.01187 MFd/km.

The frequency characteristics of the line resistance and reactance were also determined between 10 and 130 c.p.s. The results are given in fig.21 and 20. In the above frequency range, the positive sequence resistance increases by 1.5 times, while the zero sequence resistance increases by 8 to 10 times. The measured values of the positive sequence resistance and inductance as well as the line capacitance at 50 c.p.s. are sufficiently close to the values of zero sequence taken in the project. The measured values of zero sequence parameters, and especially the resistance considerably differ from the values taken in the project which were calculated by Carson's formula. (See Table III).

While the line was being tested, corona losses were measured on the line sections Eastern Substation -switching station No.3 (117 km) and Eastern Substation - switching station No.2 (391 km). The maximum value of the losses during hoar frosts which were measured on these sections is equal to 15-16 kw/km for three-phases, while on the test line in Leningrad this figure amounted to 18 kw/km for similar weather conditions. The losses on the line in clear weather were measured at 3 kw/km for three-phase, while on the test line it was 0.6 kw/km. The discrepancy is explained by the fact that the conductors on the Kuibishev-Moscow line during measurement were in the process of "aging", which lasts for 6 to 12 months.

The voltage was measured at various points along the unloaded transmission line. In doing so, voltage was applied to various lengths of open line from the Moscow end with different numbers of shunt reactors connected.

Table IV

Operating conditions	Voltage on 400 kv buses, kv: Switching station No.2	Kuibishev hydroelectric station
1 391 km section connected at Moscow end, without reactors	480 - 510	-
2 The same, 150 MVAR of reactors connected to switching station No.2	400	-
3 815 section connected at Moscow end, without reactors		800
4 The same, 150 MVAR of reactors connected to switching station No.2 at Kuibishev hydroelectric station	420	415

The line is usually connected for operation at the Moscow end with two reactors connected to the line; then the Kuibishev Hydroelectric Station is synchronized.

The measurement of internal overvoltages for the block transmission scheme of one circuit without series compensation is of interest. Results of the most severe tests are as follows: with 635 km of open line conditions were created whereby the voltage at the beginning of the line before the breaker cleared was 1.5 V phase. The line with a reactor at the middle switching station was connected to the Moscow end. The reactor was then disconnected. This increased the voltage throughout the line. After a short time when the voltage at the beginning of the line reached the above mentioned value of 1.5 V phase, the open line was cleared by an air blast breaker at the Moscow end. The voltage across the circuit breaker contacts in disconnecting the open line for the above mentioned conditions reached 2.6 V phase (where V phase is equal to $\frac{420}{\sqrt{3}}$ kv). The breaker did not arc back.

The largest overvoltages were measured in disconnecting the transmission line with a minimum of generators connected for a single line-to-ground fault on the Eastern Substation 400 kv buses. This fault was liquidated by clearing 591 km of line with the air breakers at the middle switching station (see fig.22).

Five such tests were conducted. The results of two tests, in which the largest overvoltages were measured, are given in table V. Per unit voltages are given, the base being 420 kv. The first to clear was breaker B_3 at the Eastern Substation, and after it, breaker B_5 at the middle switching station.

For the above conditions the air breaker at the middle switching station successfully cleared the line without any arcing back.

In the course of tests, 14 faults were imposed.

Three of them were solid faults and 5 were arcing to check the action of the relay protection. The carrier-current relays and single phase automatic reclosing functioned properly. Self-synchronizing tests for the generators at the Kuibishev Hydroelectric Station were conducted. When the generators had less than 50% of their rated load they fell into synchronism instantaneously. For loads exceeding 50% rated, they pulled into synchronism after slipping for about 16 to 17 seconds. Current surges during the self-synchronizing process did not exceed 300% of rated. Tests were conducted to study the clearing of an arcing groung fault when disconnecting only the faulted phase. Many such faults were imposed on line sections from 117 to 815 km long. The results were quite positive confirming the possibility of using single phase automatically reclosing for 400 kv line sections up to 500 km in length.

Studies of the carrier current channels along the 400 kv conductors indicated that the anticipated interference levels were exaggerated, the actual interference level being 2.5 nepiers below their design values.

During the summer of 1956 there were very many thunder storms along the line route. Nevertheless, the line was never disconnected on this account.

Since 1953 galloping conductors were noticed eight times. In one case, all three phases of a span galloped with an amplitude of 7 to 8 meters. In another case, one phase of a span galloped with an amplitude of 2 to 4 meters. One phase of the transition across the Ustinski reservoir, 1000 meters long, galloped with an amplitude of 4 to 5 meters.

After changing over in 1955 from the earlier designed checkerboard arrangement for the spacers to the group arrangement, no defects in operation were noticed.

Studies show that the dampers, which are to prevent the wires from vibrating entirely serve their function. The vibration protection scheme for long spans also justified itself.

The insulation and line accessories did not show any signs of failures or defects while conducting tests on the line.

On the whole, the 400 kv lines 815 and 890 km long were put into service quite normally. The good performance of the line in 1956 confirms the propositions made by Soviet engineers in working out the design in 1950-1952.

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The problems to be encountered in the future in the field of large high-voltage a.c. transmission systems are as follows:

1) to improve the solutions to the problem that were already made, and to reduce the cost of 400 kv transmission systems;

2) to work out problems connected with converting the 400 kv lines already in service for operation at 500 kv, since it is possible to reduce the value of the internal overvoltage. Thereby the insulation of the installed

equipment will be more fully utilized;

3) to develop the theory of using a still higher a.c. voltage of 600-750 kv; to carry out the necessary research and to design equipment for this voltage level that will provide for a further increase in the capacity and length of the transmission system.

Table II

Technical and economic characteristics of Soviet 400 kv lines in design and construction

Continued from the table II

1	2	3	4	5	6		7	8	9	10	11		12	13	14
N	Line	Number of circuits	Phase cross-section of aluminium-steel conductors mm²	Span m	Design conditions		Type of suspension tower	Weight of suspension tower tons	Type of suspension clamp	Type of foundation for suspension tower	Angle-strain towers		Steel expenditure per km including foundation tons	Characteristic of right of way	Remarks
					Wind pressure on conductors kg/m²	Weight of sleet load kg/m					Type	Weight tons			
1	Kuibishev-Moscow	2	3x480/60	460 425	40	0.5 1.15	H-Frame	7.3	Releasing	All concrete	Bar	23.0-27.5	29.5	Level	In operation
2	Kuibishev-Tatnjeft	1	3x480/60	400	46	1.15	Ditto	8.6	Ditto	Reinforced concrete piles and footings	Ditto	23.0-27.5	28.7	Ditto	Under construction
3	Tatnjeft-Zlatowust	1	3x480/60	400	46	1.15	H-Frame supported with guys	7.2	Ditto	Ditto	Ditto	23.0-27-5	27.2	Mountainous	Ditto
4	Stalingrad-Moscow	2	3x480/60	400	46	1.15	H-Frame	8.6	Ditto	Ditto	Ditto	23.0-27.5	29.4	Level	Ditto
5	Stalingrad-Donbass	1	2x712/93	370	57	1.15	Single post T-Frame	4.3	Ditto	Ditto	H-Frame	13.0	18.3	Ditto	±400 kv D.C.line
6	Troitsk-Cheljabinsk	1	3x480/60	400	46	1.15	H-Frame	8.6	Ditto	Ditto	Bar	23.0-27.5	31.0	Level	design data
7	Votkinsk-Sverdlovsk	1	3x400/50	390	46	1.15	H-Frame supported with guys	7.2	Limited holding strength	Ditto	None	None	23.4	Mountainous	Ditto
8	Bratsck-Irkutsck	2	3x480/60	415	57	1.15	Ditto 50% H-Frame 50%	7.2 8.6	Ditto	Ditto	Ditto	Ditto	28.0	Ditto	Ditto

Table III

C_{11} MFd/km		C_w MFd/km		R_1 ohm/km		L_1 mH/km		R_o ohm/km			L_o mH/km		
Test value	Design value	Test value	Design value	Test value	Design value	Test value	Design value	Test value, length: 117 km	Test value, length: 391 km	Design value	Test value, length: 117 km	Test value, length: 391 km	Design value
0.00878	0.00867	0.01187	0.01250	0.0236	0.0220	0.946	0.948	0.365	0.257	0.171	3.48	3.46	2.97

Table V

Trail:	Conditions	Measured voltages when disconnecting breaker B_3 at the Eastern Station						Measured voltages when disconnecting breaker B_5 afterwards at the middle switching station			
		Voltage on breaker B_3 contacts		Voltage at point U_3		Voltage at point U_4		Voltage on breaker B_5 contacts		Voltage at point U_5	
		Peak	steady-state	Peak	Steady-state	Peak	Steady-state	Peak	Steady-state	Peak	Steady-state
1.	Line cleared without single line-to-ground fault	1.55	1.22	2.20	1.82	2.10	1.78	2.55	1.28	1.95	1.40
2.	Line cleared with single line-to-ground fault at point 3 near Eastern Station buses	1.80	1.30	2.60	2.10	2.50	2.0	3.30	1.40	2.00	1.40

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1. A.V. Mirolubov The Kuibishev-Moscow 400 kv transmission.
CIGRE. 1952, paper N 408.

2. A.A.Gogolin, K.K. Levitski, A.V. Mirolubov, S.S. Rokotjan, V.N. Sergeev, B.V. Sokolov
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CIGRE. 1956, paper N 413.

3. A.I. Kolpakova, M.L. Levinstein, G.A. Slavine
Recovery voltages during fault clearing on long transmission lines with series capacitors.
CIGRE. 1956, paper N 142.

4. V.M. Yermolenko, S.G. Petrov
The effect of series-capacitor compensation on relay operation.
CIGRE. 1956, paper N 323.

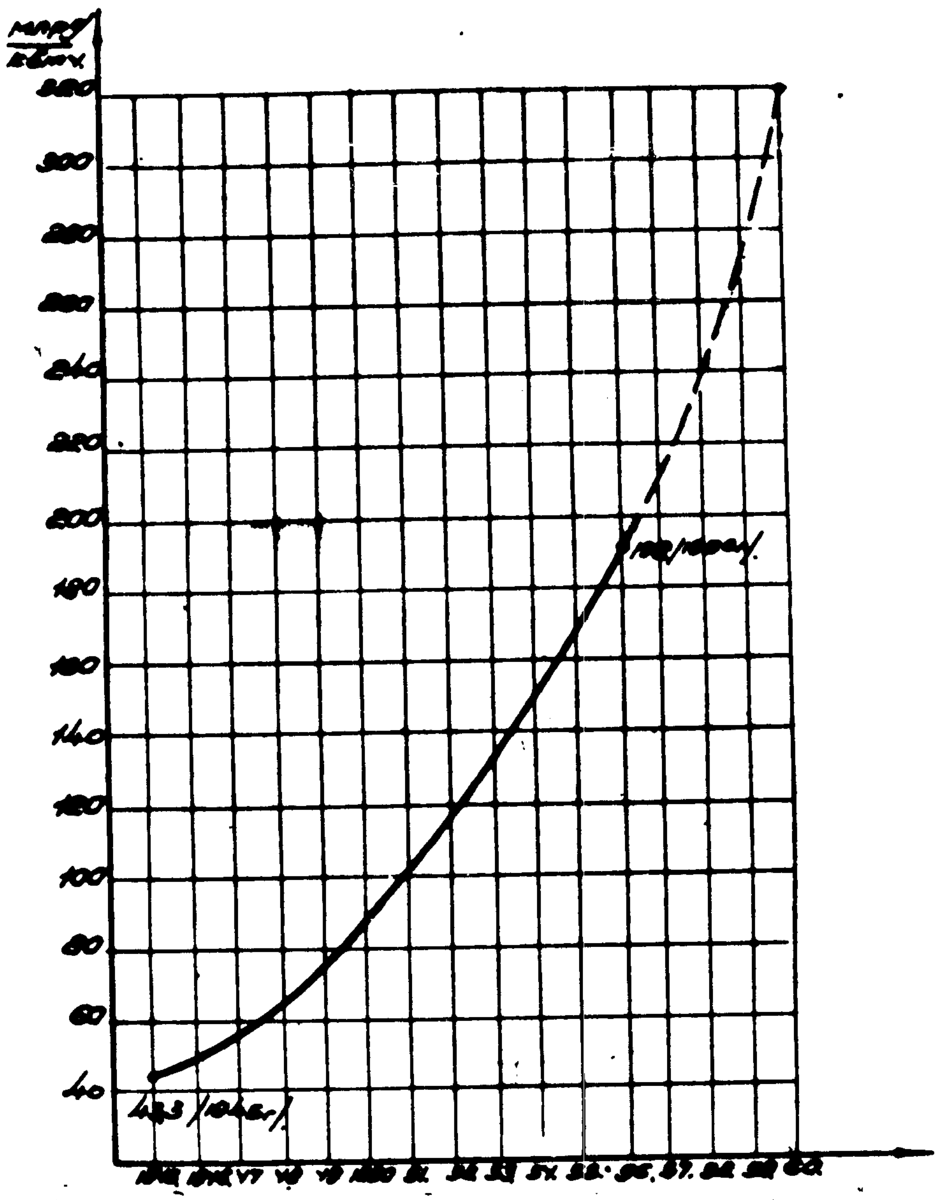

Fig. 1 - Growth in the output of the power stations in the Soviet Union during the post-war years

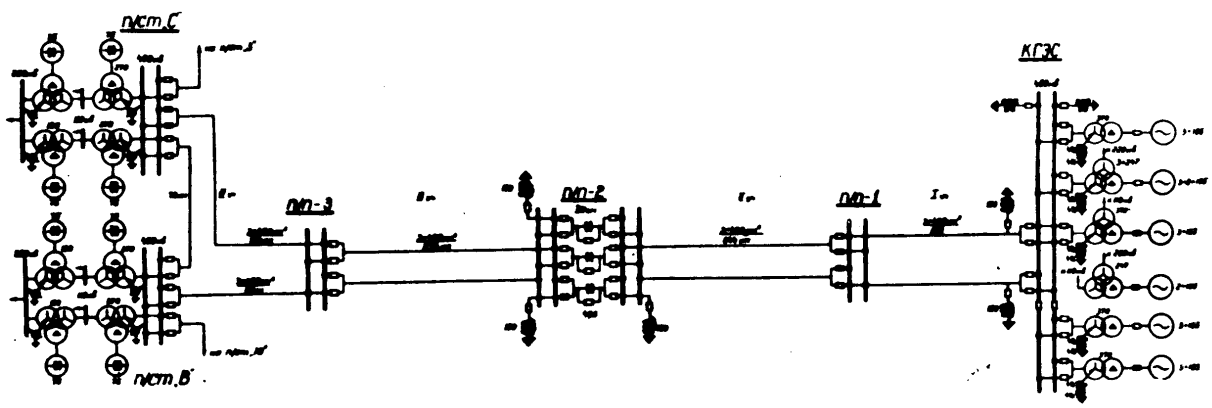

Fig.2 - Scheme of the Kuibishev-Moscow transmission system

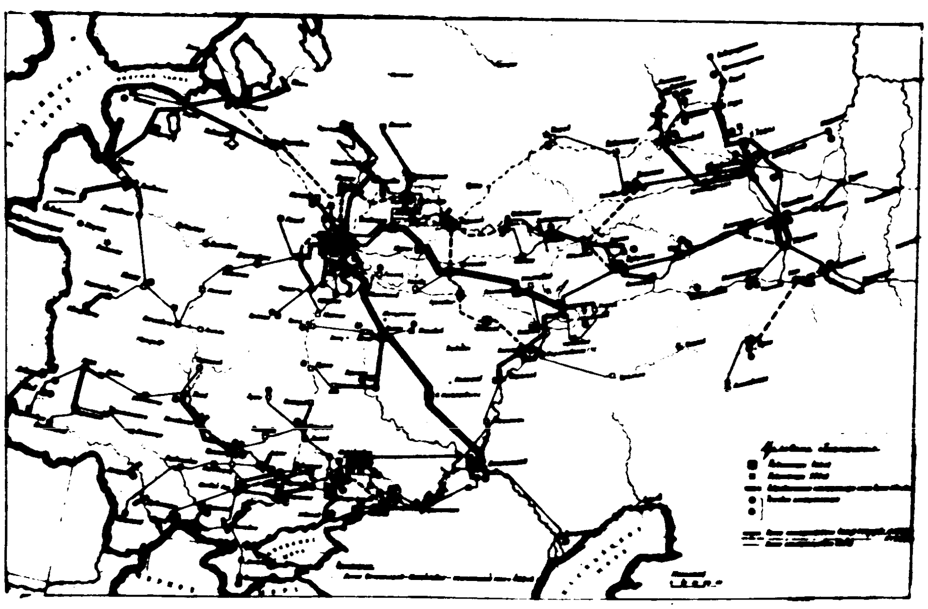

Fig. 3 - Diagram of the main 400 and 220 kv circuits in the consolidated power system of the European part of the U.S.S.R. as planned for 1965

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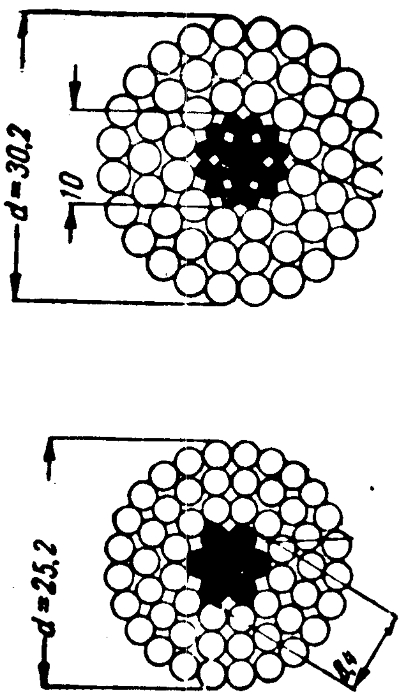

Fig. 4 - Design of conductors used for 400 kv lines

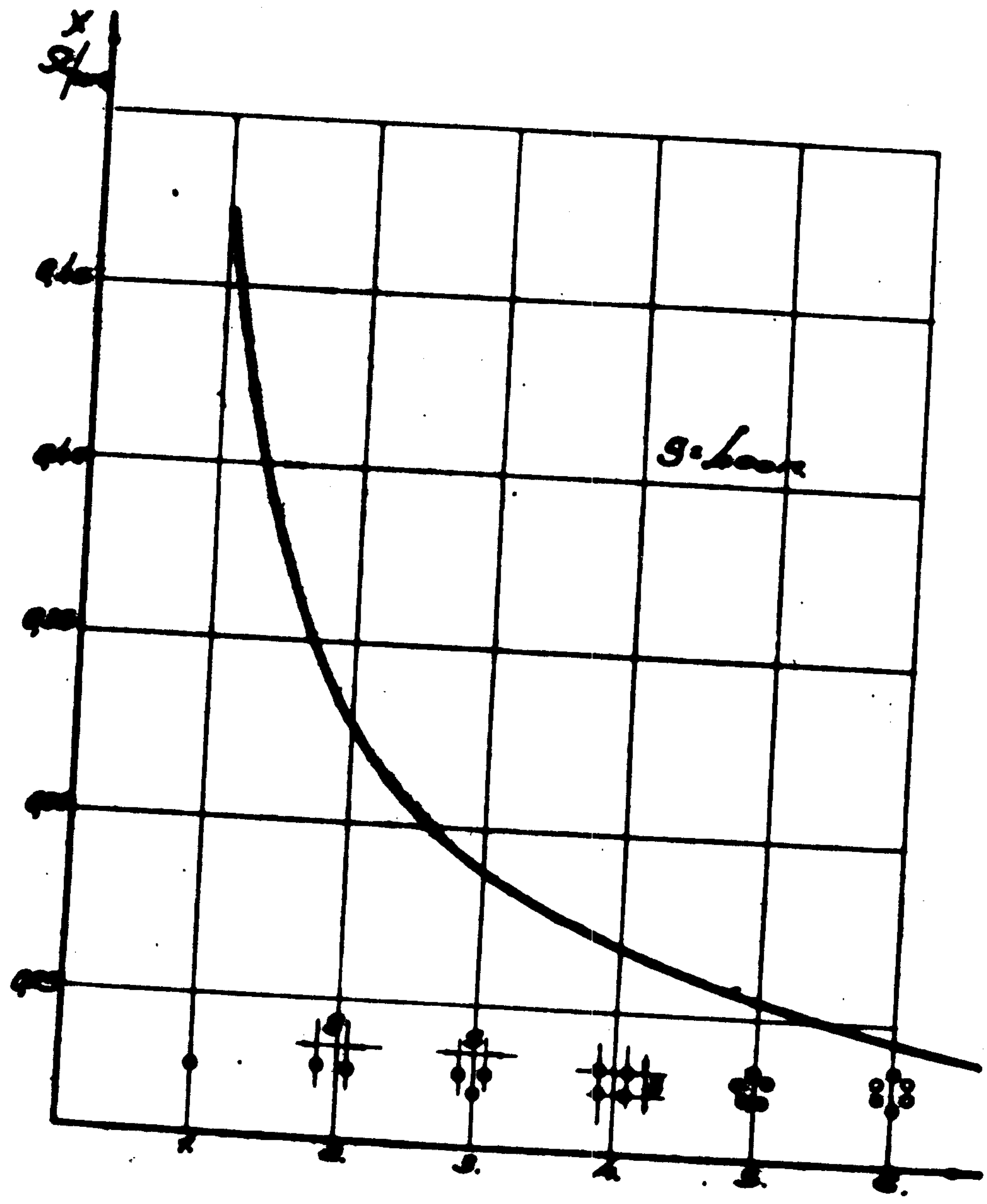

Fig. 5 - The effect of bundle conductors on the reactance of 400 kv lines

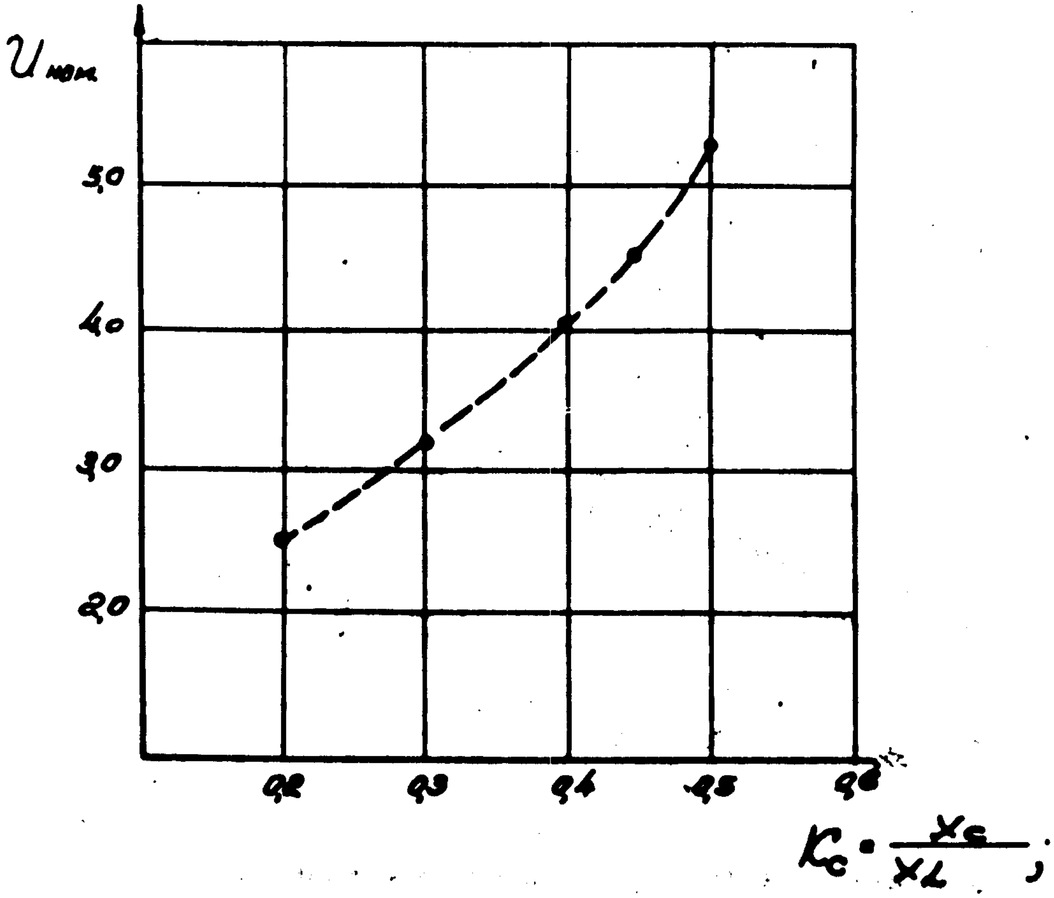

Fig. 6 - The effect of series capacitor compensation on the level of internal overvoltages in a 400 kv system;

Notes to Fig. 6:

1 - In calculating the curve, the reactances of the sending and receiving systems were taken into account as was the increase in impedance of the series capacitor installation after clearing the faulted section.

2 - In calculating the curve the voltage on the capacitors at the moment the fault is cleared was taken to be equal to the breakdown voltage of the protective gap across the series capacitor installation.

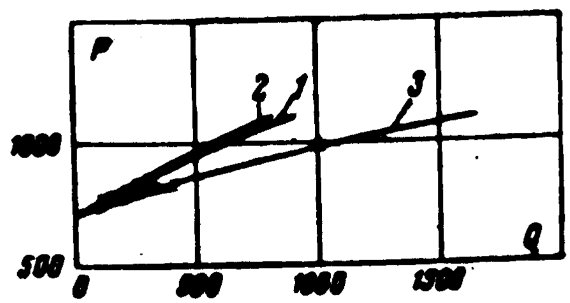

FIG 7 - The capacity of a 400 kv transmission system 1000 km long as a function of the series capacitor rating (1), the compensated synchronous condenser rating (2), and the uncompensated synchronous condenser rating (3)

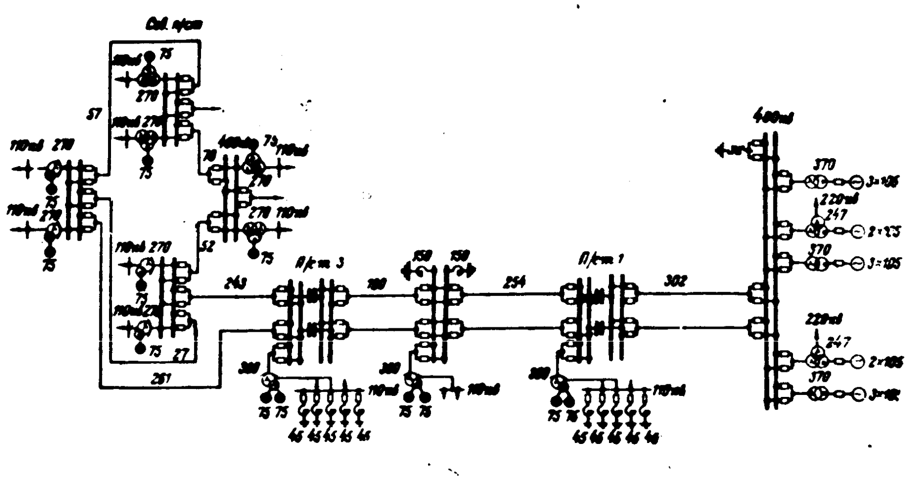

Fig. 8 - Schemo of the 400 kv Stalingrad-Moscow transmission line

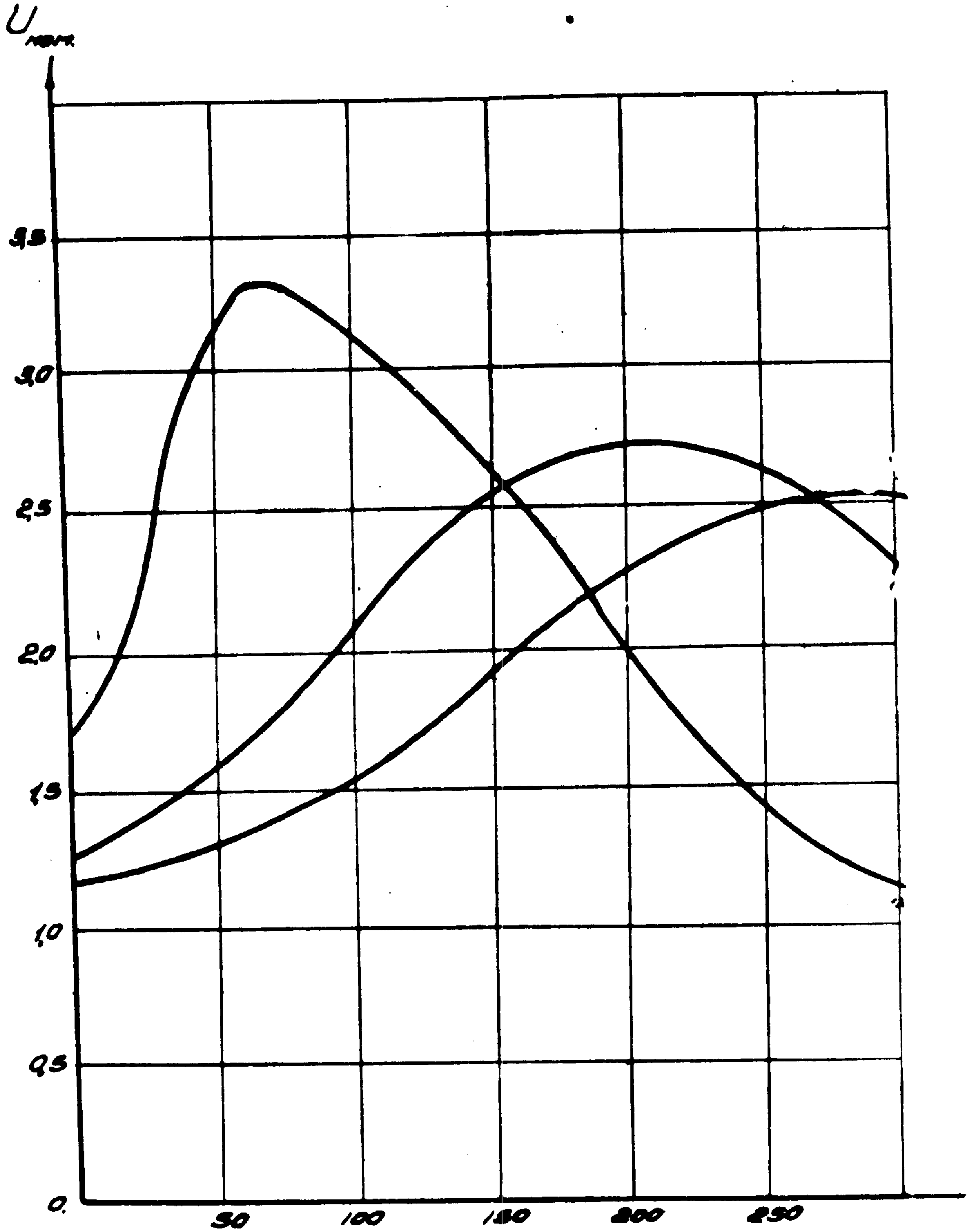

Fig. 9 - The effect of shunt reactors on the internal over-voltage level of a 400 kv system

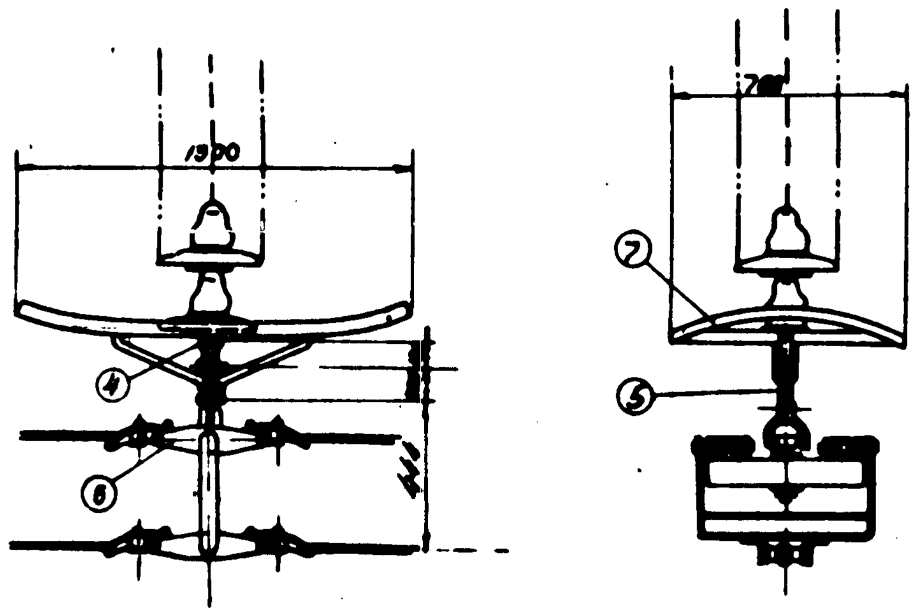

Fig.10 - Releasing mechanism for three conductors of a 400 kv line

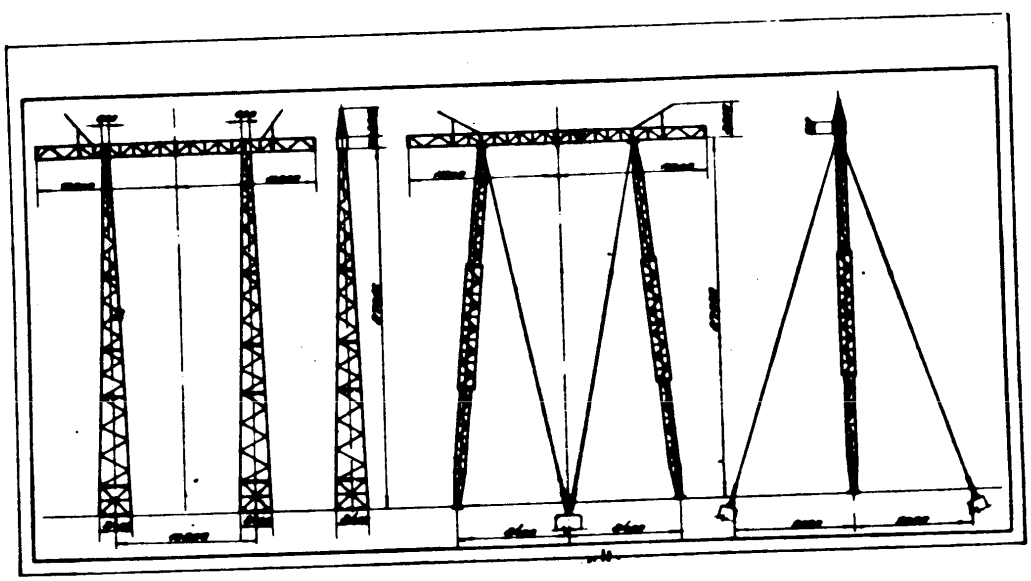

Fig.11 - Suspension towers for 400 kv lines

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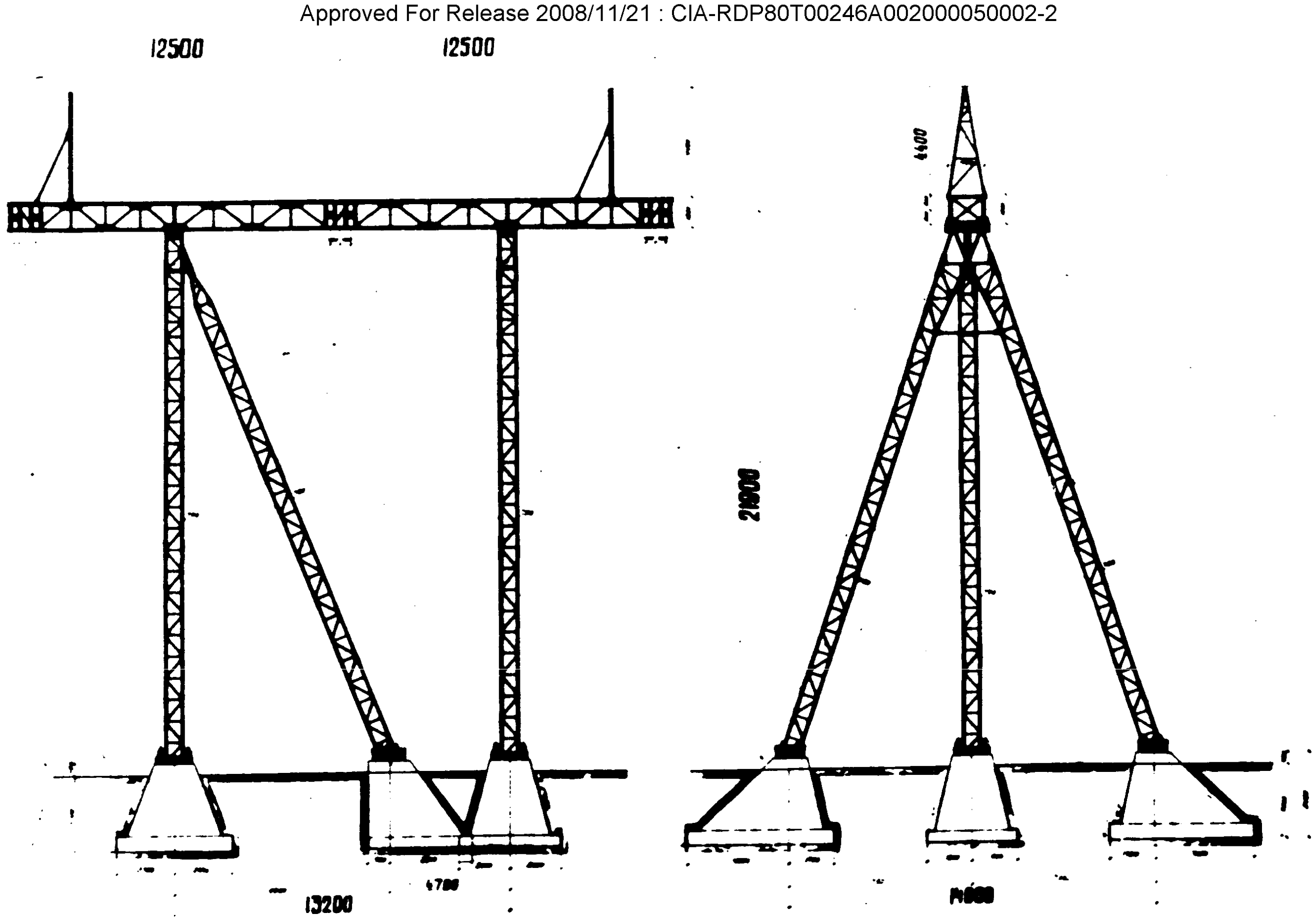

Fig.12 - Angle-strain tower for a 400 kv line

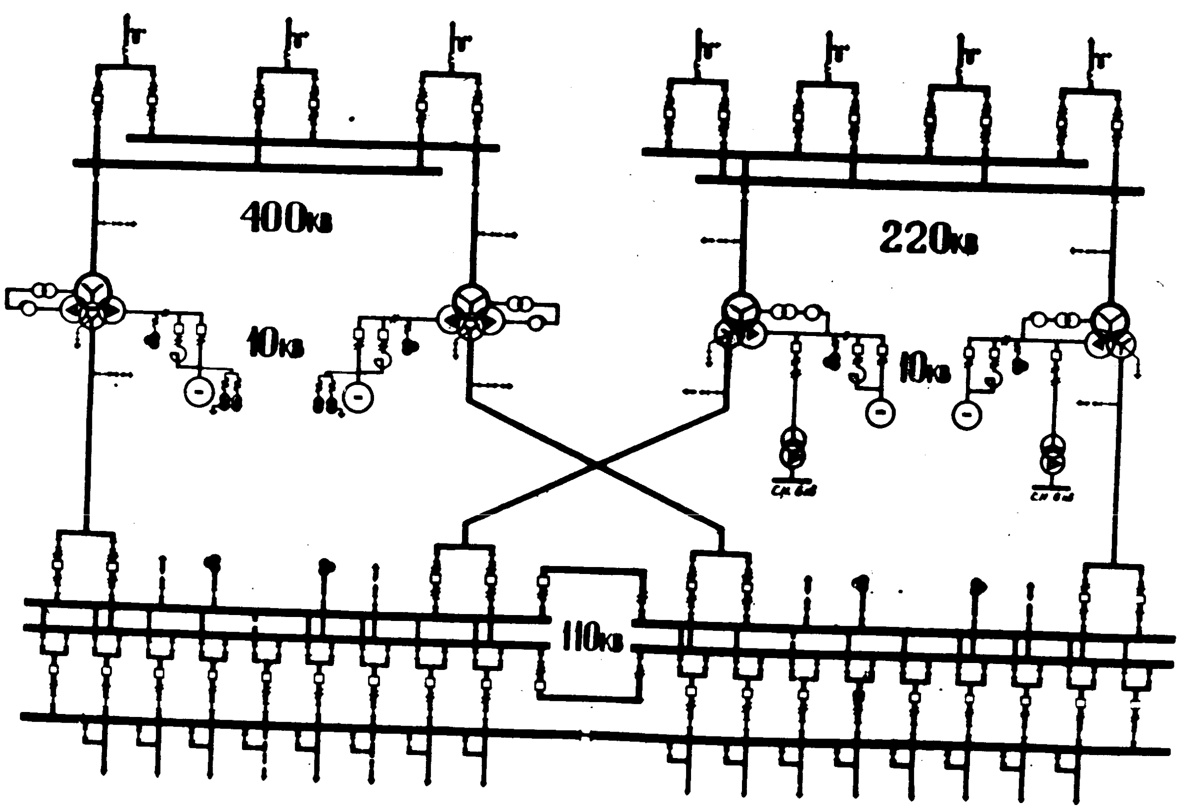

Fig.14 - Scheme of the 400 kv Northern Substation

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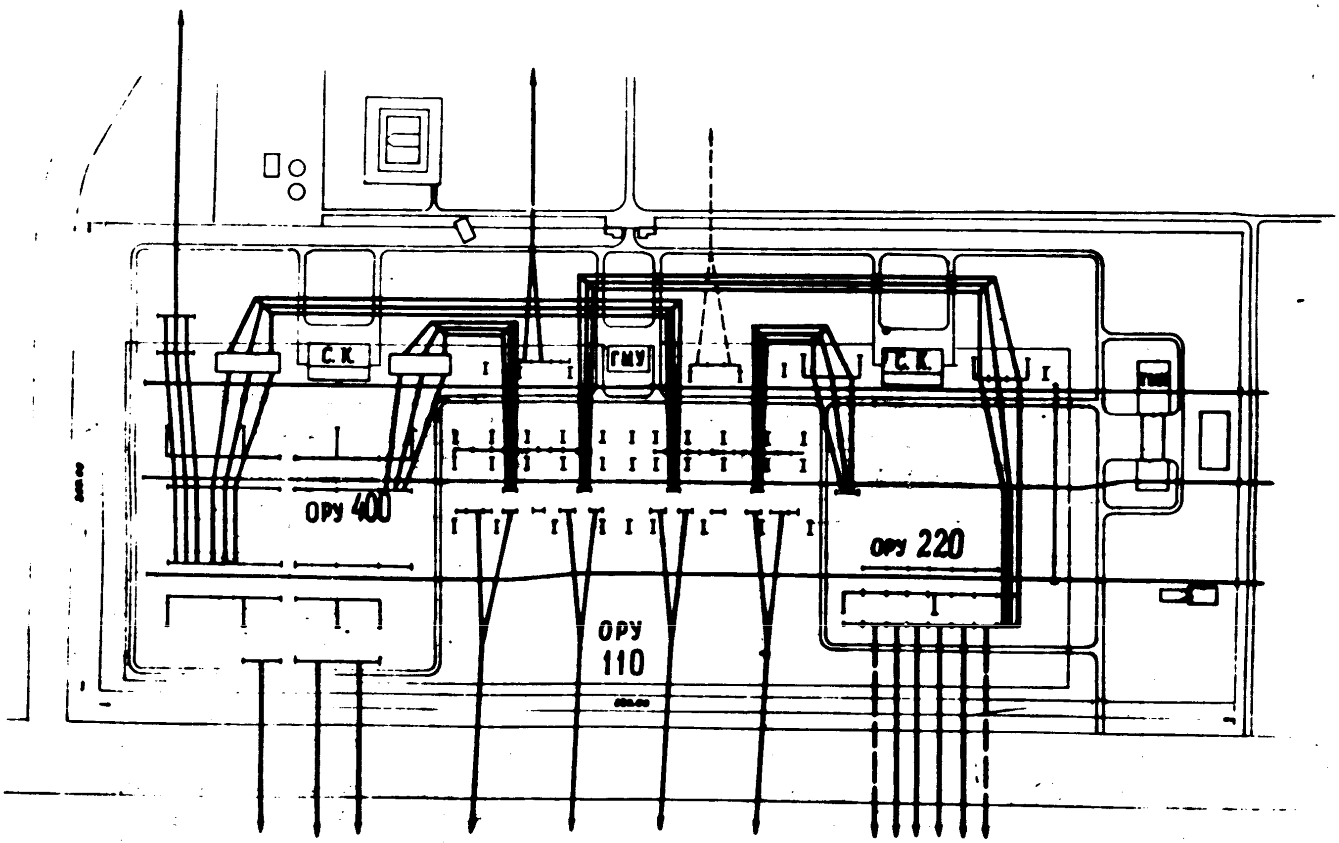

Fig.15 - Plan for a 400/110/220 kv substation

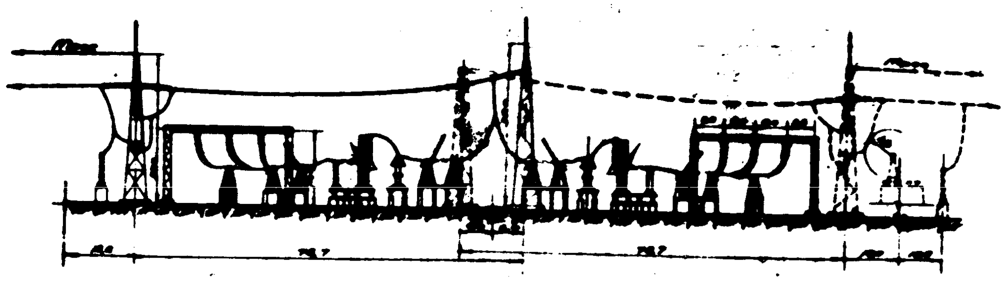

Fig.16 - Section of the new design of 400 kv outdoor switchgear

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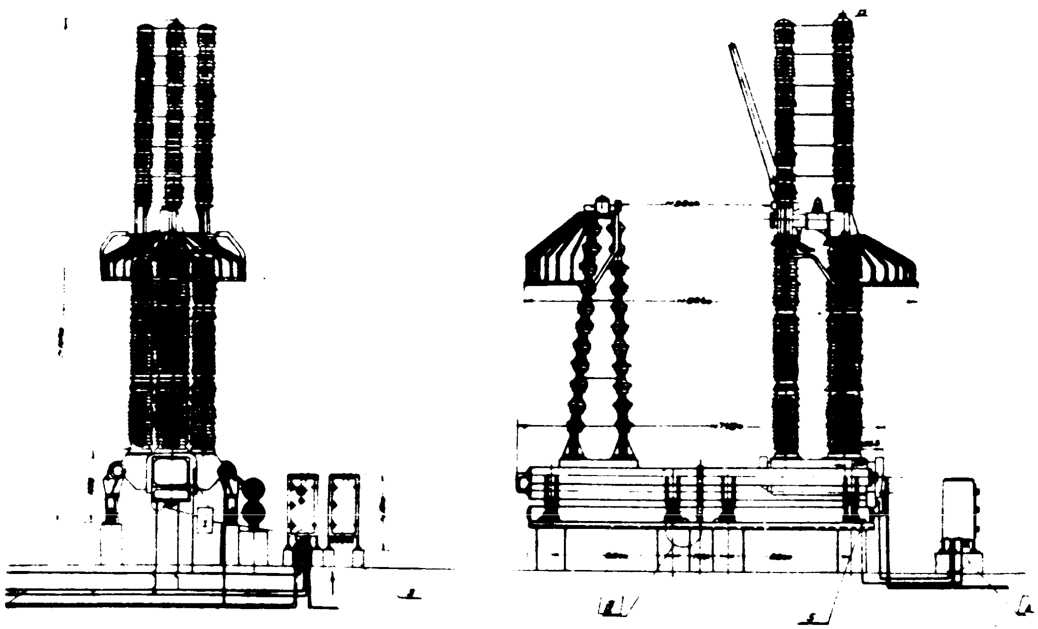

Fig.17 - 400 kv air breakers

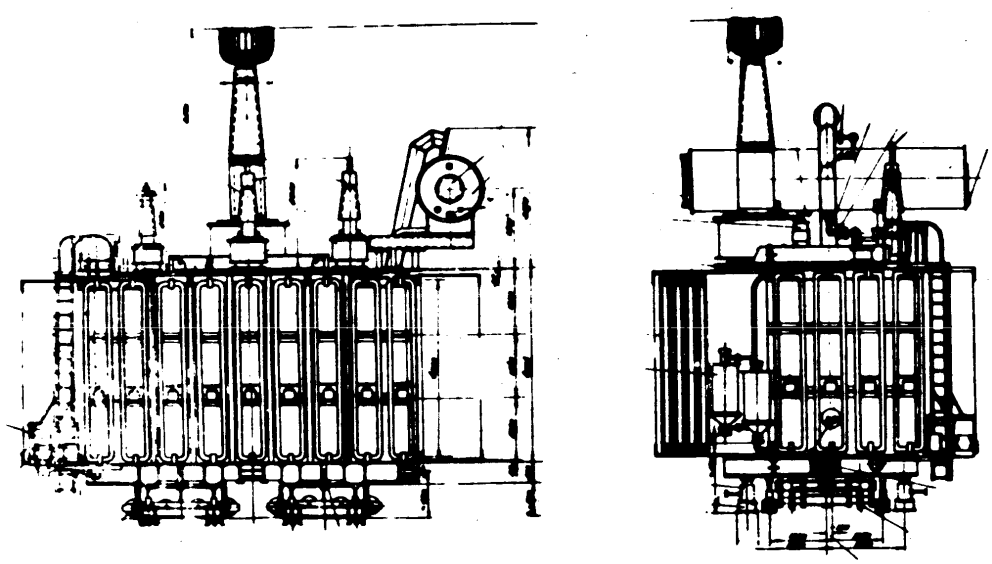

Fig.18 - 400 kv step-down power transformer

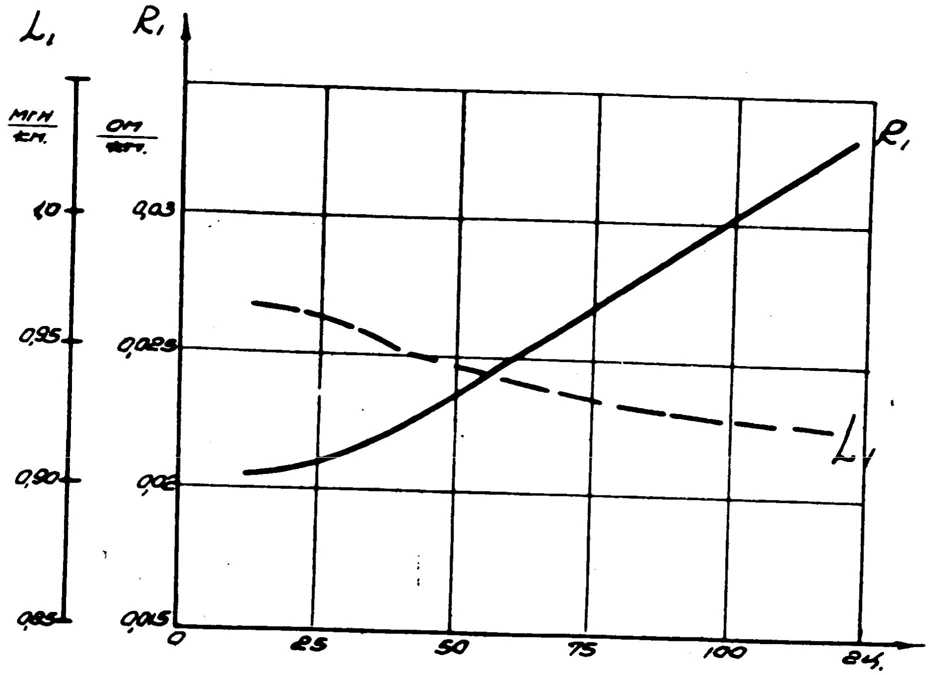

Fig.20 - Frequency characteristic of positive sequence resistance and reactance of a 400 kv line

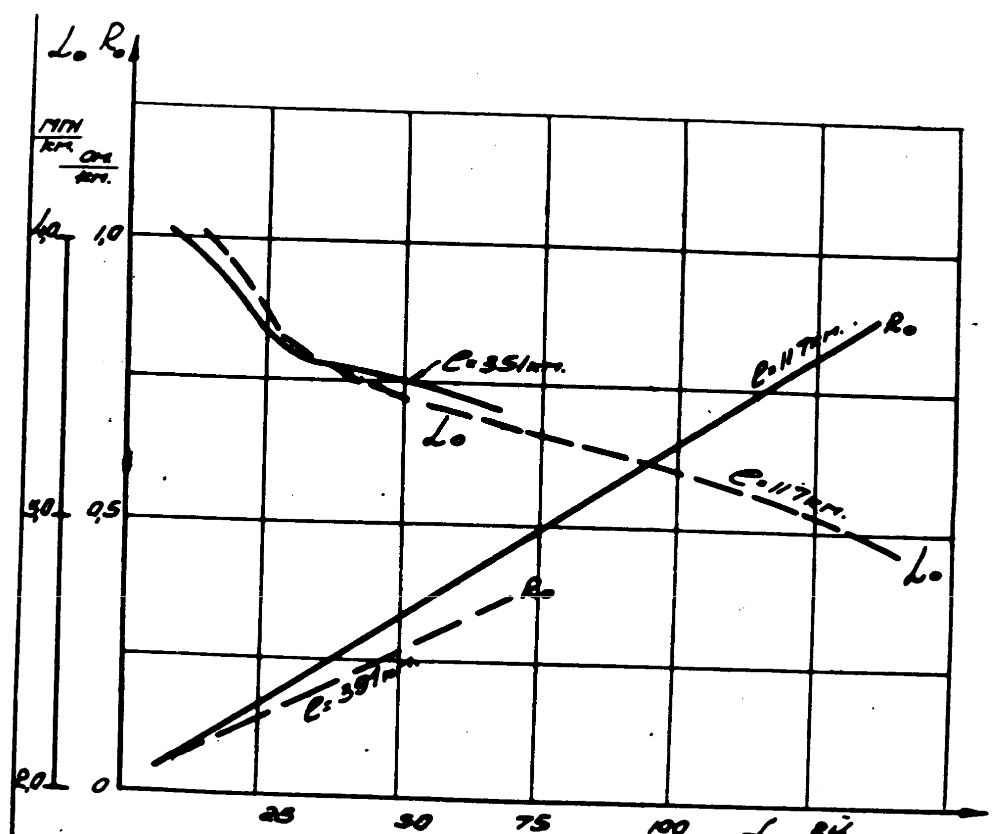

Fig.21 - Frequency characteristic of zero sequence resistance and reactance of a 400 kv line

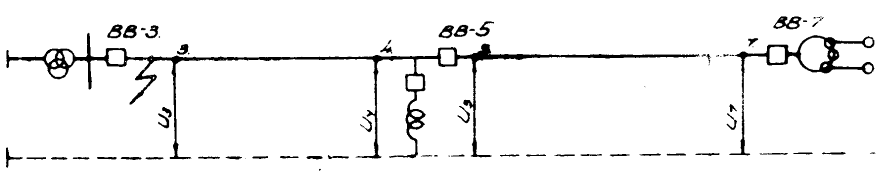

Fig. 22- Scheme for testing an air breaker on interruption of transmission

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